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# Les Houches 2021: quick status

J. Huston

Energy Frontier un-hibernation



September 2, 2021



# The Path to Precision

- It's clear by now that copious new physics isn't jumping out at us
- In order to better understand the SM, and look for something beyond, we have to extend our precision (as well as our kinematic reach)
- This may involve improvements on both the theoretical and experimental fronts, for example
  - ▢ measurements of photons, leptons, jets, boosted objects
  - ▢ extension of NNLO to 2->3 processes
  - ▢ (more) inclusion of EW effects
  - ▢ more precise PDFs, better understanding of precision of PDFs. and of  $\alpha_s(m_\tau)$



These efforts are not confined to Les Houches. even while Snowmass was hibernating, multiple workshops/programs ongoing, such as last week's Taming the Accuracy of Event Generators tackling similar problems.



# We have an LOI!

## Snowmass LOI Les Houches Wishlist:

T. Hobbs, A. Huss, J. Huston, S. Jones, S. Kallweit

August 31 2020

Contact: J. Huston, huston@msu.edu

### 1 Introduction

One of the legacies of the Les Houches workshops has been the precision standard model wishlist [1, 2]. This is an attempt to (1) summarize the state of the art for higher order QCD and EW calculations and (2) to determine the calculations needed for the full exploitation of the full-luminosity LHC. This list includes calculations that may not necessarily be accessible with current-day techniques, but that can be obtained in a reasonable time frame, given sufficient theoretical effort. The justification for the effort is the expected statistical and systematic precision of the relevant experimental measurements, and the importance of better theoretical predictions for those measurements.

Given the longer-term nature of the wishlist (2040), it seems natural to fit it into the Snowmass21 framework, by extending the scope to physics expected at a 33 or 100 TeV collider. This can also be considered the extension of the work conducted in Snowmass13 [3]. The higher energies allow for an extension of the kinematic reach, for example, for a high  $p_T$  Higgs boson to a region where new physics effects may become evident. Cross sections below the kinematic edge may reach a 1% or better precision. Scales well above the  $W/Z$  boson mass will result in the importance of higher order EW corrections, as well as combined QCD+EW corrections. QCD calculations at  $N^3LO$  will require PDFs at a similar order, as well as a combined QCD+EW evolution of these PDFs. The treatment of  $W/Z$  bosons, as well as top quarks, as partons present in the proton may become necessary.

Another future accelerator that will require increased theoretical precision is the Electron-Ion-Collider (EIC), where higher-order  $\alpha_s(m_Z)$  and electroweak corrections will have to be well-understood. Data taken at the EIC will also have the potential to provide more precise PDF information, both at  $x \gtrsim 10^{-4}$  as well as high  $x$ , that will be crucial for precision predictions at a 33 or 100 TeV collider. The greater objective is to generalize beyond 1-D distributions, so further theoretical effort is required to develop factorization theorems, especially for robust extraction and interpretation of multi-dimensional distributions like TMDs and GPDs.

In this LOI, we propose a coherent program between Les Houches 2021 and Snowmass21 to explore the higher-order calculations needed for 33/100 TeV and a projection of the technical capabilities available by that time. Experience at 13 TeV, and that expected at the HL-LHC, will be crucial in this extrapolation. The calculations needed will depend not only on the experimental errors expected, but the impact of higher order corrections at these higher energies.

...in particular, there is a lot of overlap with what people are trying to accomplish in the Snowmass exercise

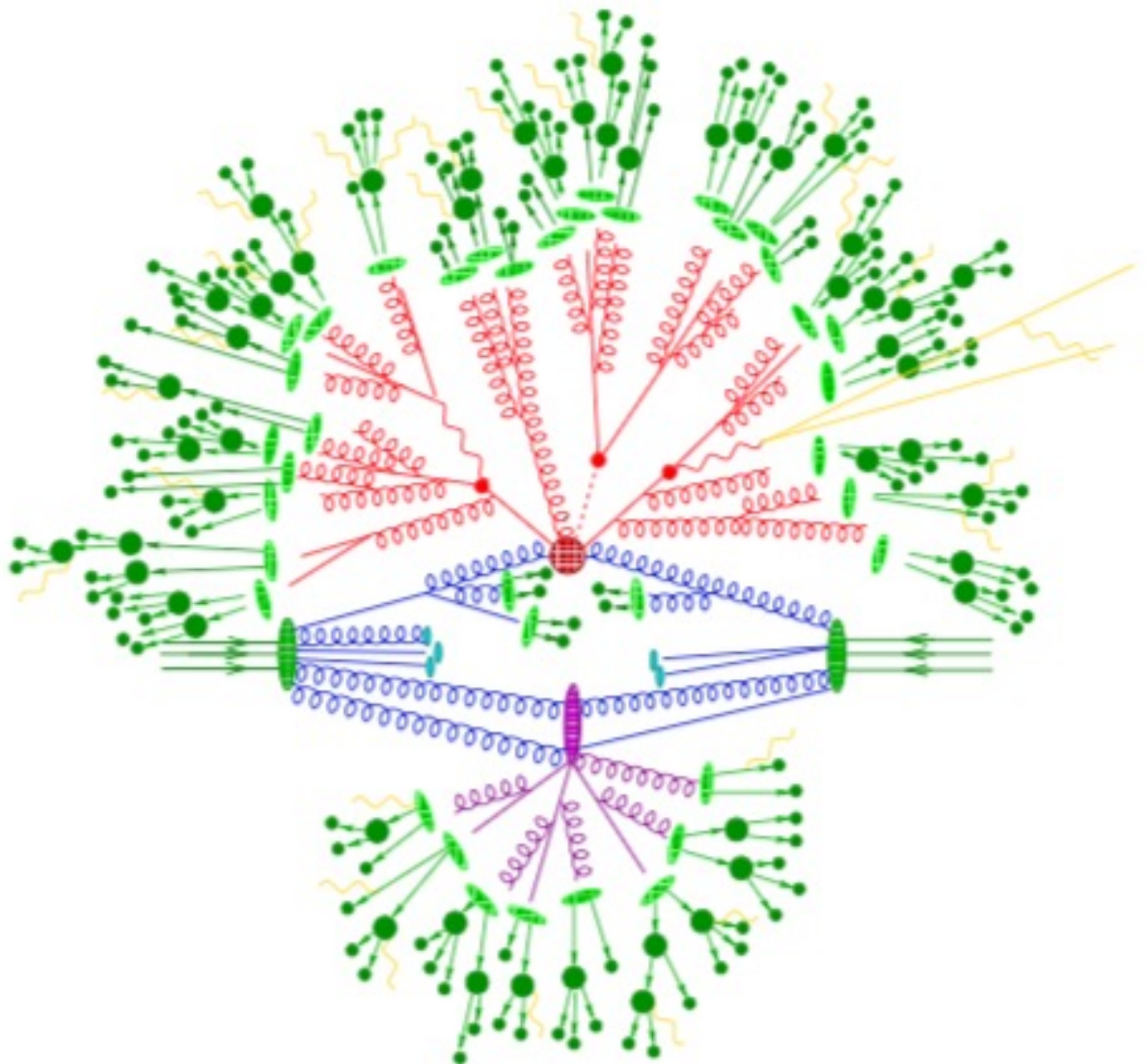
EF05: Precision QCD

EF06: Hadronic Structure and Forward QCD



# All aspects of the event are important

- Higher order matrix element
- PDFs
- Parton shower accuracy
- Non-perturbative corrections
- (Unfolding)





# Theoretical predictions

**Theory must reach comparable precision target**

Sotnikov RadCor/Loopfest 21

NNLO QCD and NLO EW corrections generally required

( $\oplus$  parton shower, resummation, etc.)

$$\sigma \sim \underbrace{\sigma_{\text{LO}} \left( 1 + \alpha_s \sigma^{(1)} \right)}_{\text{NLO}} + \overbrace{\alpha_s^2 \sigma^{(2)}}^{\text{NNLO}} + \mathcal{O}(\alpha_s^3)$$

naively  $\lesssim 1\%$

NB: both EW and non-perturbative corrections can be similar size to NNLO corrections;

...in addition to the calculation of higher order matrix elements, also need precision for PDFs and for  $\alpha_s(m_Z)$

...where there is a restriction of phase space, need resummation

...where possible, need a translation into a form that may be more amenable to experimental comparison, i.e. ME+PS

...Les Houches accord/concensus: ME+PS predictions should agree with underlying fixed order prediction in non-Sudakov regions



# Les Houches precision wishlist (2019)

## NLO automation and (N)NLO techniques

### 1 Update on the precision Standard Model wish list <sup>1</sup>

Identifying key observables and processes that require improved theoretical input has been a key part of the Les Houches programme. In this contribution we briefly summarise progress since the previous report in 2017 and explore the possibilities for further advancements. We also provide an estimate of the experimental uncertainties for a few key processes. A summary of this sort is perhaps unique in the field and serves a useful purpose for both practitioners in the field and for other interested readers. Given the amount of work that has been, and is being, done, this summary will no doubt be incomplete, and we apologize for any omissions.<sup>2</sup>

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<sup>1</sup> A. Huss, J. Huston, S. Jones, S. Kallweit

<sup>2</sup> The Les Houches Disclaimer

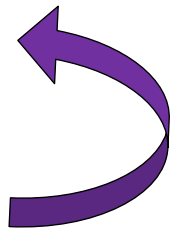


# Calculations: input to Les Houches

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Experimenters  $\longleftrightarrow$  Theorists

- theory predictions needed to exploit physics potential, i.e. V+n jets at NNLO
- form of theory predictions needed, i.e. NNLO grids, K-factors, inclusion in MEPS programs...
- experimental precision achievable in foreseeable future  $\rightarrow$  drives theoretical precision needed





Adding loops, in particular 2- $\rightarrow$ 3 at NNLO

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arXiv:2003.01700 (will be updated for 2021 report)

process	known	desired
$pp \rightarrow H$	$N^3\text{LO}_{\text{HTL}}$ (incl.)	$N^3\text{LO}_{\text{HTL}}$ (partial results available) $\text{NNLO}_{\text{QCD}}$
	$N^{(1,1)}\text{LO}_{\text{QCD} \otimes \text{EW}}^{(\text{HTL})}$	
	$\text{NNLO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}}$	
$pp \rightarrow H + j$	$\text{NNLO}_{\text{HTL}}$	$\text{NNLO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	$\text{NLO}_{\text{QCD}}$	
$pp \rightarrow H + 2j$	$\text{NLO}_{\text{HTL}} \otimes \text{LO}_{\text{QCD}}$	$\text{NNLO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ $\text{NNLO}_{\text{QCD}}^{(\text{VBF})} + \text{NLO}_{\text{EW}}^{(\text{VBF})}$
	$N^3\text{LO}_{\text{QCD}}^{(\text{VBF}^*)}$ (incl.)	
	$\text{NNLO}_{\text{QCD}}^{(\text{VBF}^*)}$	
	$\text{NLO}_{\text{EW}}^{(\text{VBF})}$	
$pp \rightarrow H + 3j$	$\text{NLO}_{\text{HTL}}$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	$\text{NLO}_{\text{QCD}}^{(\text{VBF})}$	
$pp \rightarrow H + V$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	$\text{NLO}_{gg \rightarrow HZ}^{(t,b)}$
$pp \rightarrow HH$	$N^3\text{LO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}}$	$\text{NLO}_{\text{EW}}$
$pp \rightarrow H + t\bar{t}$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	$\text{NNLO}_{\text{QCD}}$
$pp \rightarrow H + t/\bar{t}$	$\text{NLO}_{\text{QCD}}$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$

### Primer

- $\text{LO} \equiv \mathcal{O}(1)$ ,
- $\text{NLO QCD} \equiv \mathcal{O}(\alpha_s)$ ,
- $\text{NNLO QCD} \equiv \mathcal{O}(\alpha_s^2)$ ,
- $\text{NLO EW} \equiv \mathcal{O}(\alpha)$ ,
- $\text{NNNLO QCD} \equiv \mathcal{O}(\alpha_s^3)$ ,
- $\text{NNLO QCD+EW} \equiv \mathcal{O}(\alpha_s\alpha)$ .

Note I haven't mentioned logarithmic accuracy, which will also be important in regions with restricted phase space.

Table I.1: Precision wish list: Higgs boson final states.  $N^x\text{LO}_{\text{QCD}}^{(\text{VBF}^*)}$  means a calculation using the structure function approximation.



# Les Houches wishlist often used as motivation

## Motivation

See for example half of the talks at  
RadCor+Loopfest

- ▶ Experimental precision will increase with more statistics.
- ▶ Need two-loop amplitudes to match with NNLO precision.
- ▶ Master integrals required.
- ▶ 5-point 1-mass relevant for **W/Z/H-plus-two-jets** production at the LHC.

[See Bayu's talk for  $W + b\bar{b}$ ]

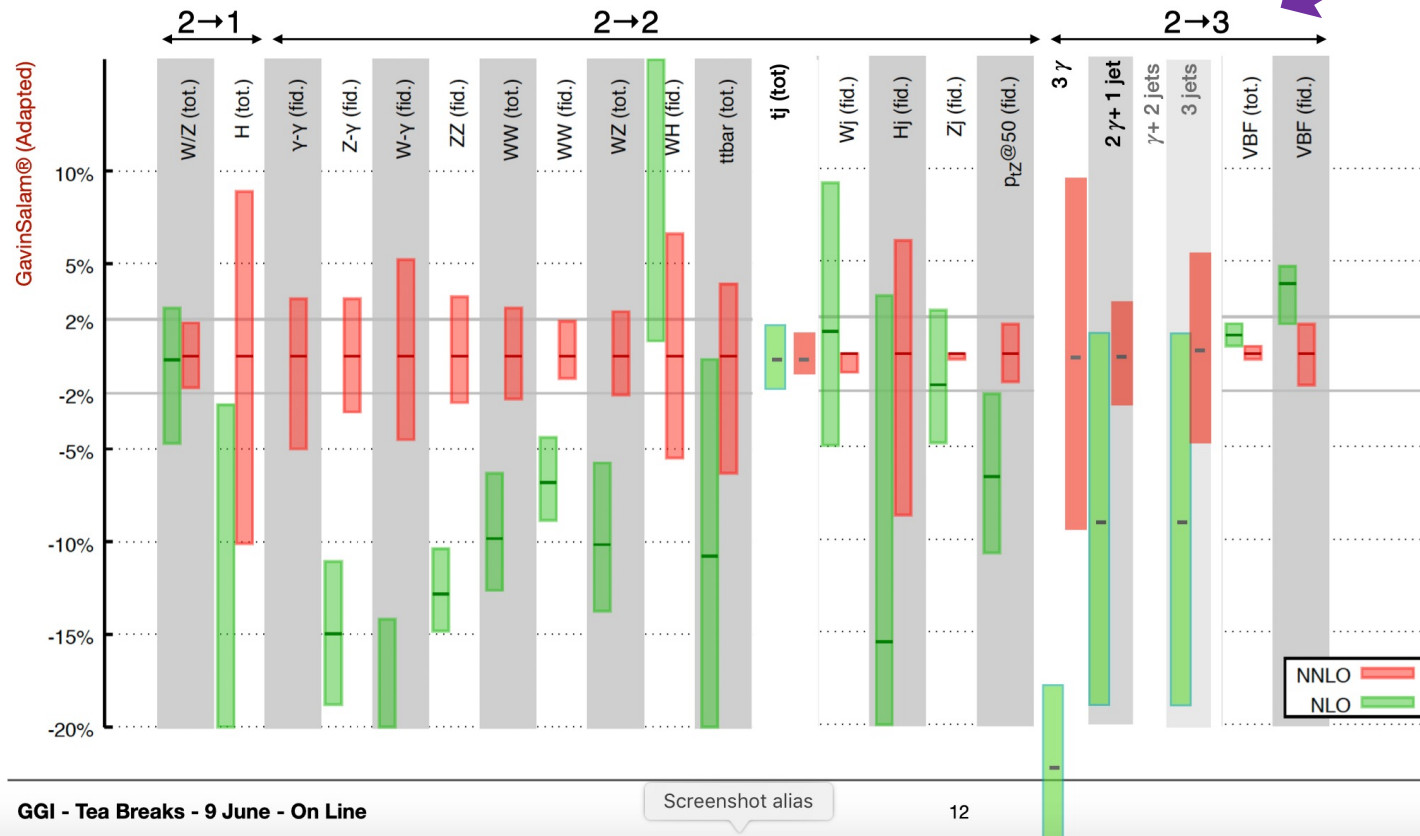
process	known	desired
⋮	⋮	⋮
$pp \rightarrow V + 2j$	$NLO_{QCD} + NLO_{EW}$ $NLO_{EW}$	$NNLO_{QCD}$
⋮	⋮	⋮
$pp \rightarrow H + 2j$	$NLO_{HTL} \otimes LO_{QCD}$ $N^3LO_{QCD}^{(VBF^*)}$ incl. $NNLO_{QCD}^{(VBF^*)}$ $NLO_{EW}^{(VBF)}$	$NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}$ $NNLO_{QCD}^{(VBF)} + NLO_{EW}^{(VBF)}$
⋮	⋮	⋮

[Les Houches precision wishlist '19]



# Fabio Maltoni talk from GGI

## Precision calculations for the LHC Status: Fixed Order



- NNLO brings us in the few percent arena
- Several NNLO computations move the central value out of the NLO uncertainties
- The 2→3 wall broken



# PDFs

- Determined from global fits to data from a wide variety of processes, both from fixed target and collider experiments, with an increasing contribution from the LHC itself

- The 3 groups are CTEQ-TEA (CT), MSHT (new acronym) and NNPDF

- Each uses on order of 4000 data points to determine the best fit PDFs and their uncertainties

□ with CT and MSHT using a Hessian formalism and NNPDF using a neural net formalism

- Each group provides regularly updated sets of PDFs

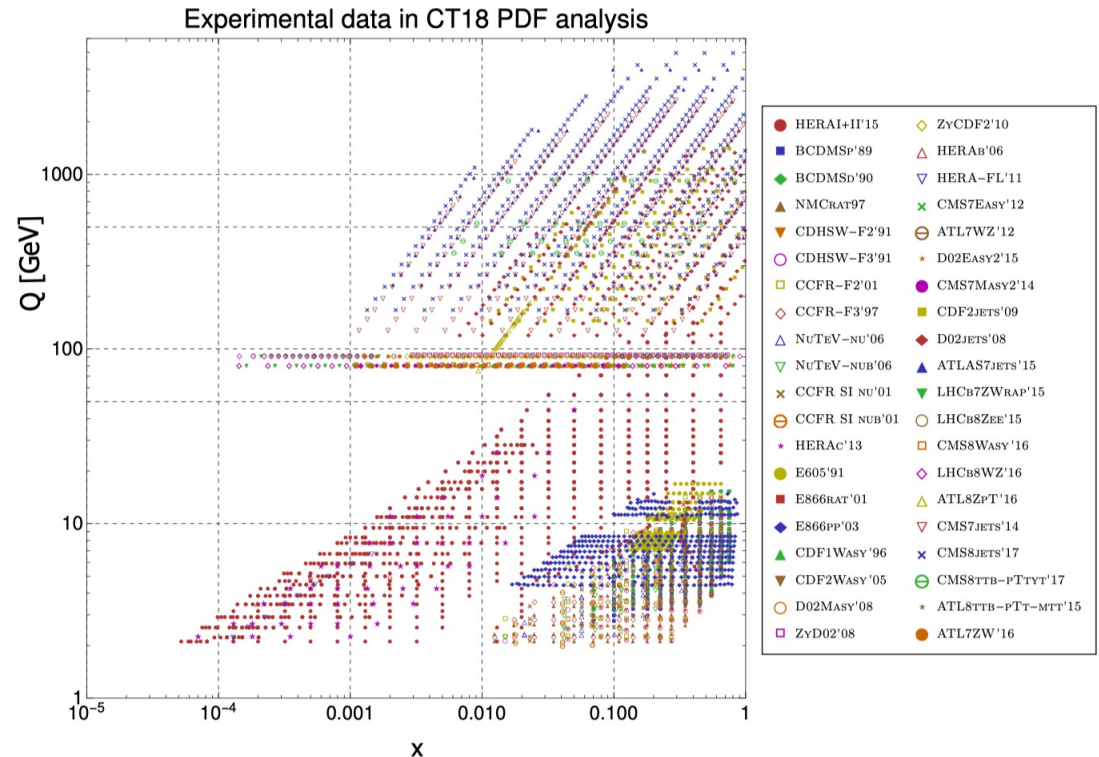


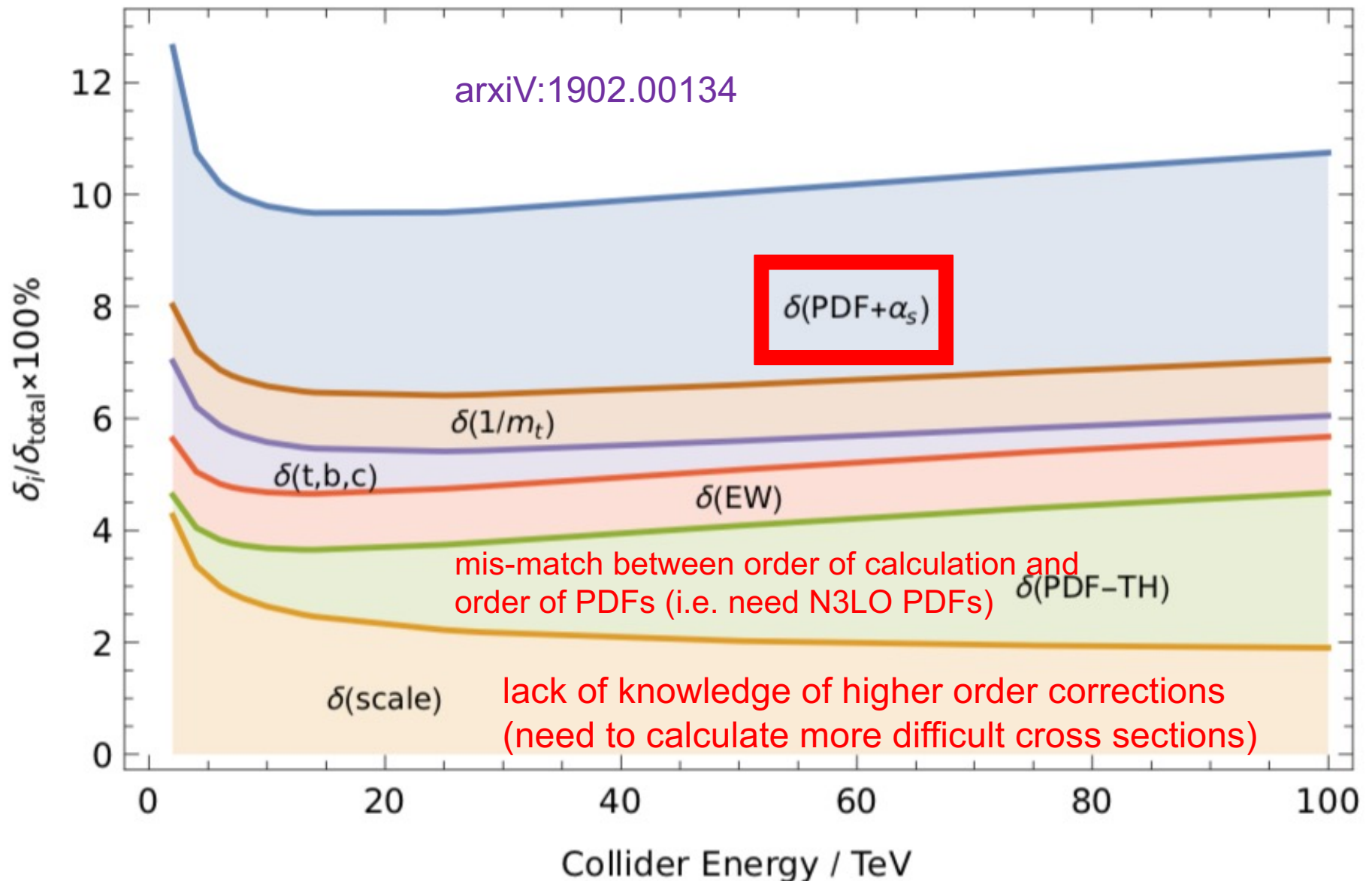
FIG. 1: The CT18 data set, represented in a space of partonic  $(x, Q)$ , based on Born-level kinematical matchings,  $(x, Q) = (x_B, Q)$ , in DIS, *etc.*. The matching conventions used here are described in Ref. [20]. Also shown are the ATLAS 7 TeV W/Z production data (ID=248), labeled ATL7WZ'12, fitted in CT18Z.

to better understand similarities and differences, it is useful to periodically perform benchmarking exercises

See Tom Cridge's talk on Wed.



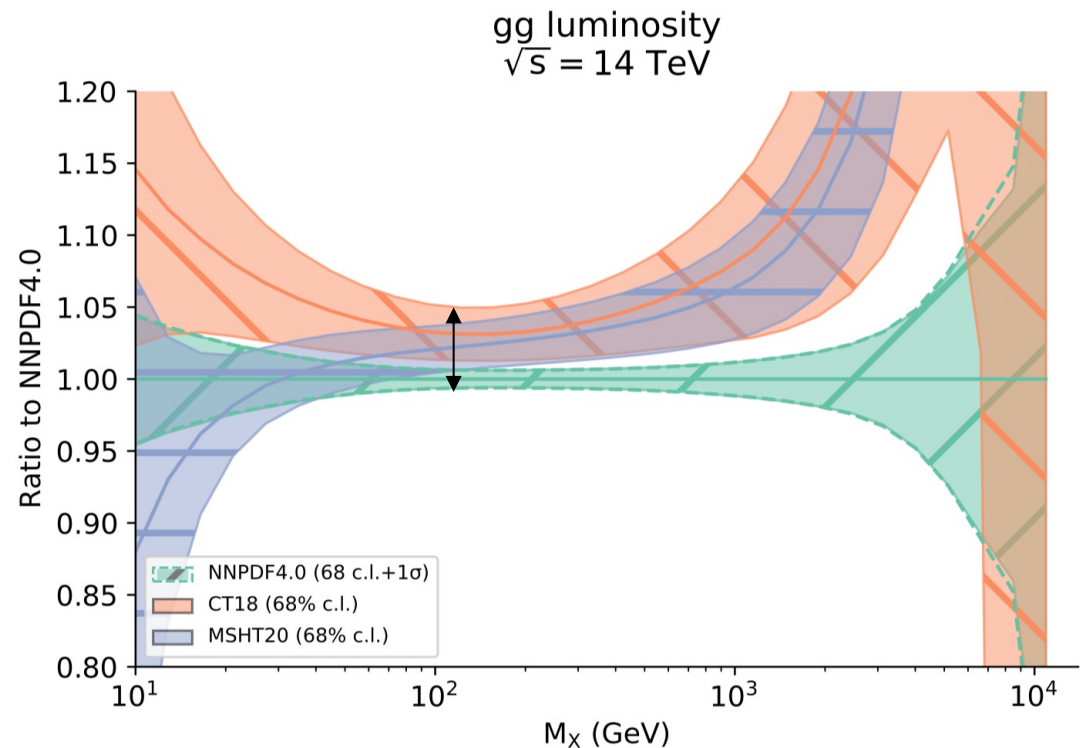
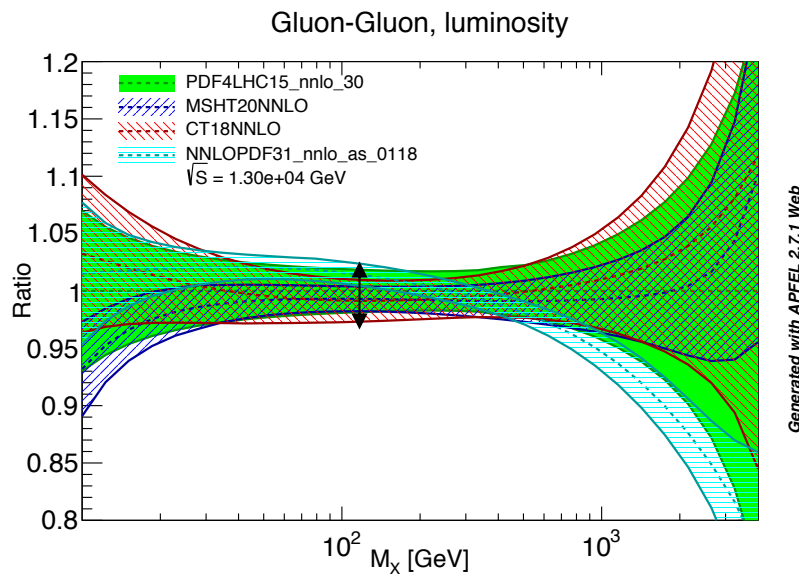
# Uncertainties (for ggF Higgs)





# PDF4LHC21 and NNPDF4.0

the situation for gg looks different for NNPDF4.0 than for 3.1; spread of central PDFs would still contribute to gg PDF uncertainty [but plan is to use NNPDF3.1 in PDF4LHC21)





# $\alpha_s(m_Z)$ uncertainties

importance of  $\alpha_s$  uncertainties depends on order of calculation, so very important for Higgs through ggF at N3LO

- LO  $\equiv \mathcal{O}(1)$ ,
- NLO QCD  $\equiv \mathcal{O}(\alpha_s)$ ,
- NNLO QCD  $\equiv \mathcal{O}(\alpha_s^2)$ ,
- NLO EW  $\equiv \mathcal{O}(\alpha)$ ,
- NNNLO QCD  $\equiv \mathcal{O}(\alpha_s^3)$ ,
- NNLO QCD+EW  $\equiv \mathcal{O}(\alpha_s \alpha)$ .

update underway;  
will not change much

$$\alpha_s(M_Z^2) = 0.1176 \pm 0.0011, \quad (\text{without lattice})$$

$$\alpha_s(M_Z^2) = 0.1182 \pm 0.0008, \quad (\text{lattice})$$

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0010.$$

My opinion is that precision of lattice will improve faster than non-lattice.

2019; 2021 update underway

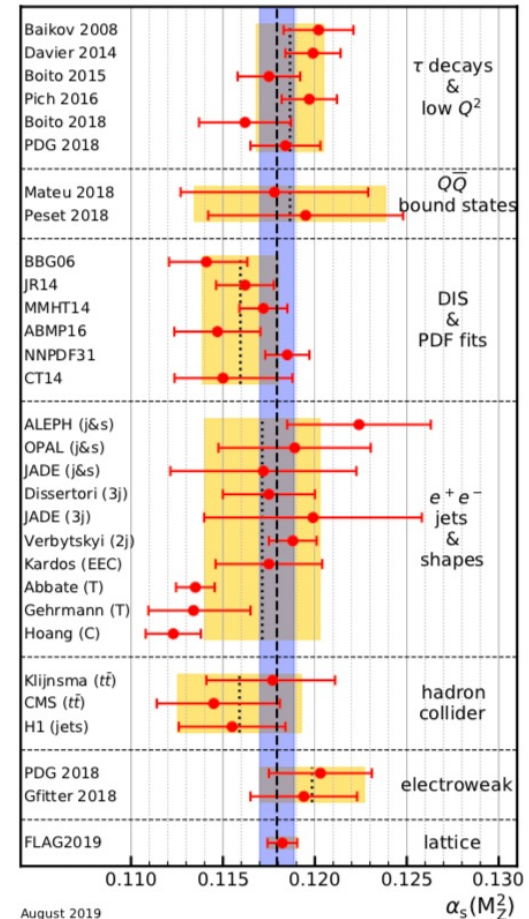
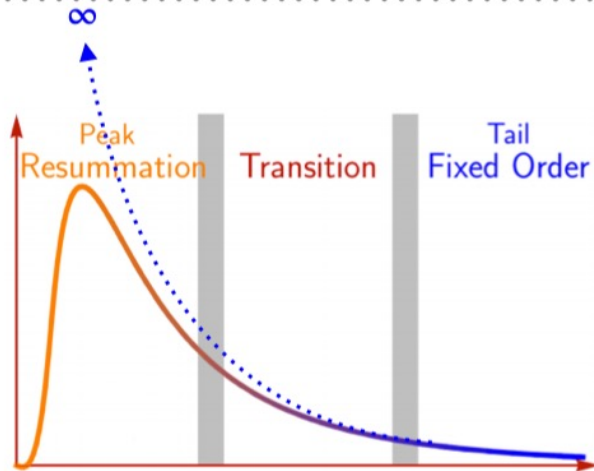


Figure 9.2: Summary of determinations of  $\alpha_s(M_Z^2)$  from the seven sub-fields discussed in the text. The yellow (light shaded) bands and dotted lines indicate the pre-average values of each sub-field. The dashed line and blue (dark shaded) band represent the final world average value of  $\alpha_s(M_Z^2)$ .

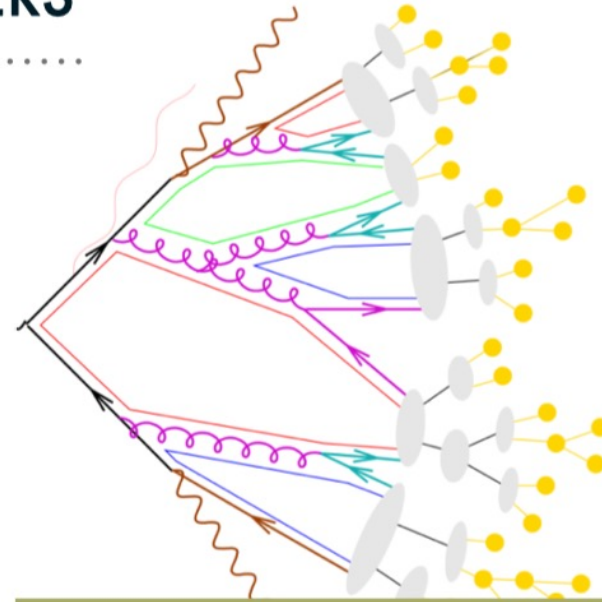


# RESUMMATION & PARTON SHOWERS



## Resummation

inclusive (analytic), tailored to specific observable with high logarithmic accuracy



## Parton Showers (PS)

exclusive (MC algorithm), general purpose + non-perturbative models

- ◉ What is the (logarithmic) **accuracy** of parton showers?
- ◉ Is it (N)**LL**? For what observable(s)?

- ◉ **crucial** to understand  $\rightsquigarrow$  design new PS

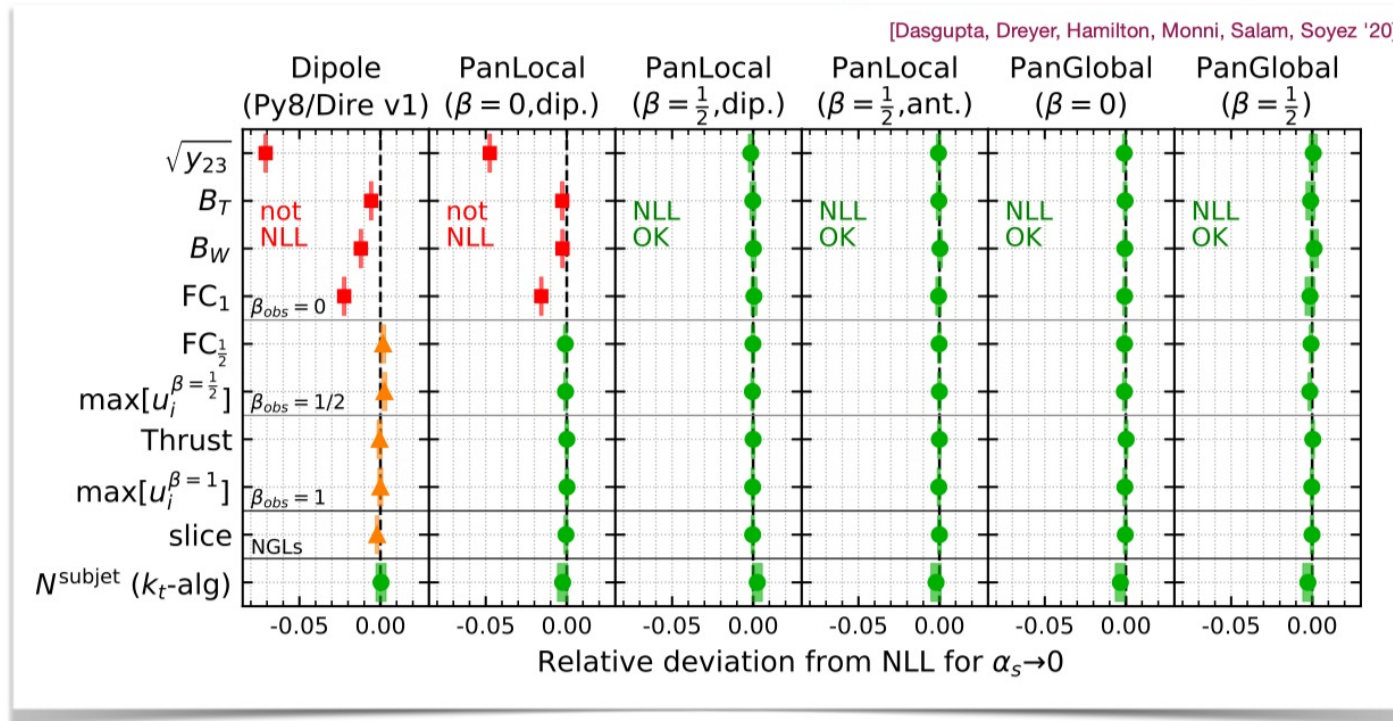
[Forshaw, Holguin, Plätzer '20] [Nagy, Soper '19] [...]  
[Dasgupta, et al. '20; Hamilton, et al. '20; Karlberg, et al. '21]



# Shower accuracy

## INVESTIGATING SHOWER ACCURACY\*

- Compare PS to NLL observables:  $\alpha_s \rightarrow 0$  for fixed  $\alpha_s L$



- Is this observables set “complete”? How to extend it for pp?
- Can this test be adopted by other groups?

G. Salam

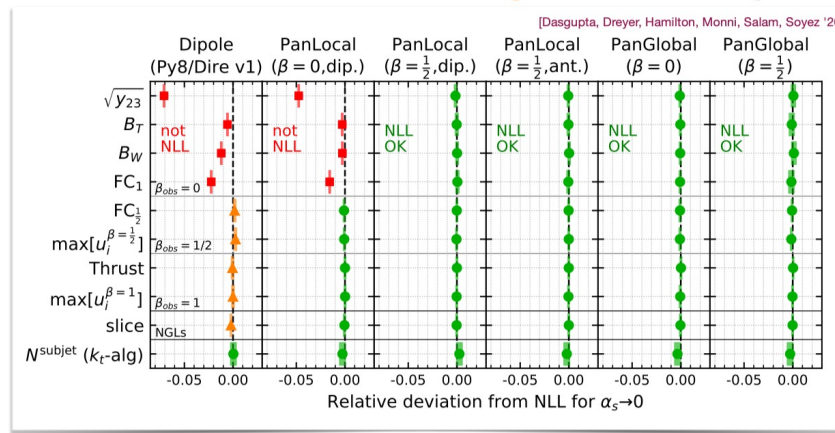
\* see also: [Nagy, Soper, '20]

# Shower accuracy

- This is in the limit of  $\alpha_s \rightarrow 0$  and  $\alpha_s L$  is constant, appropriate for testing the logarithmic accuracy.
- It would be very useful if we could provide some benchmarking of PanShowers and current showers (Herwig, Pythia, Sherpa, DIRE, Vincia,...) on a more realistic framework, such as LEP legacy data (to start with) to see/understand the differences that show up

## INVESTIGATING SHOWER ACCURACY\*

- Compare PS to NLL observables:  $\alpha_s \rightarrow 0$  for fixed  $\alpha_s L$



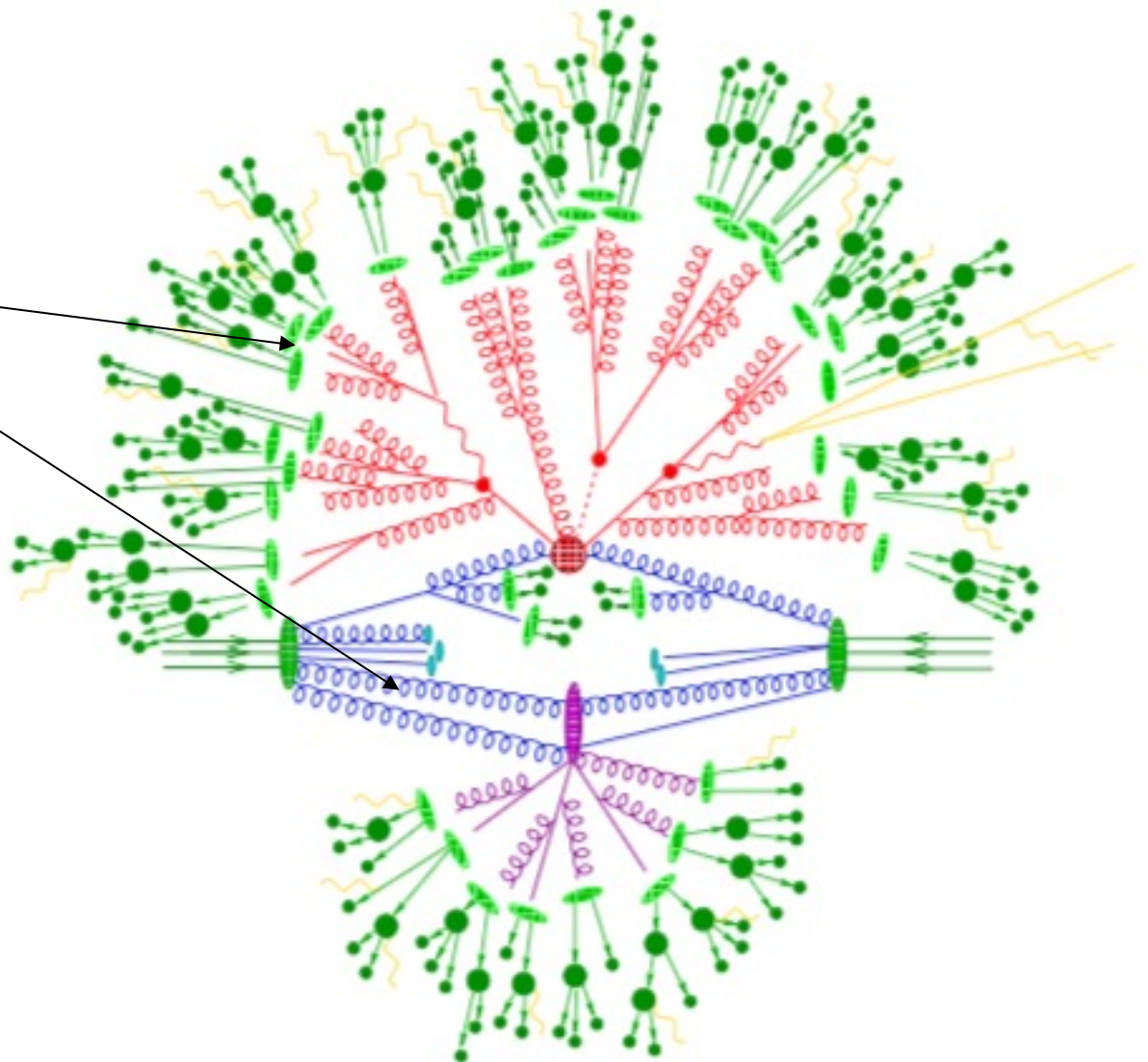
- Is this observables set “complete”? How to extend it for pp?
- Can this test be adopted by other groups?

\* see also: [Nagy, Soper, '20]



## But the event is more than the parton shower

- ...and many of the crucial differences /systematics that we see arise from the treatment of non-perturbative effects

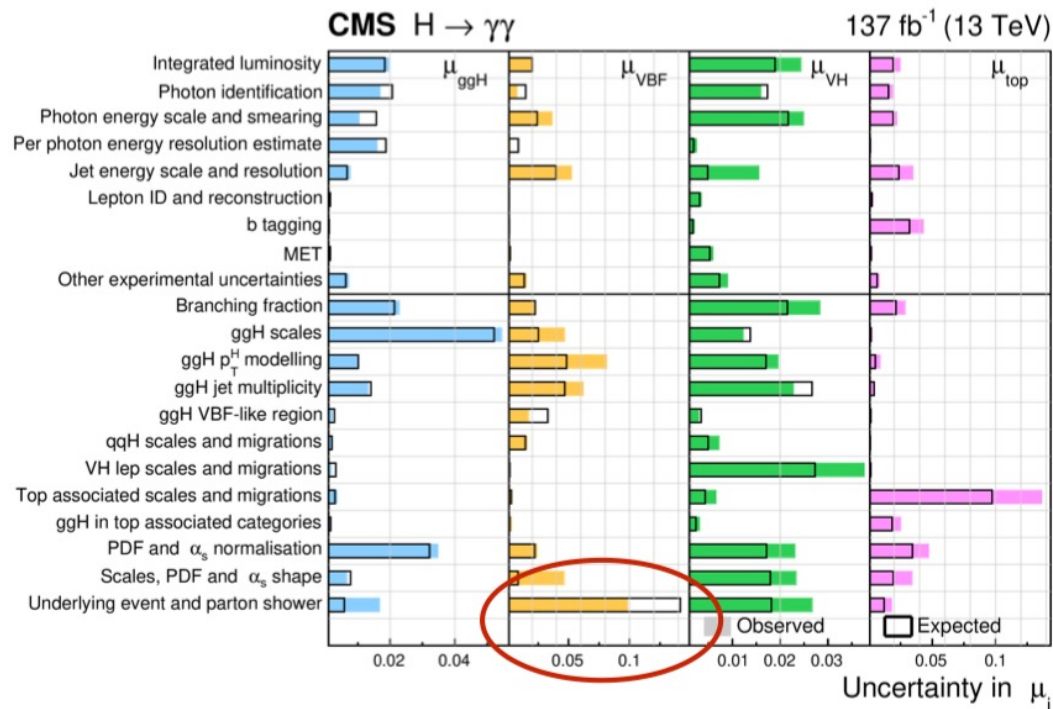




# PS/Had/UE | $H \rightarrow \gamma\gamma$ VBF

ATLAS-CONF-2020-026

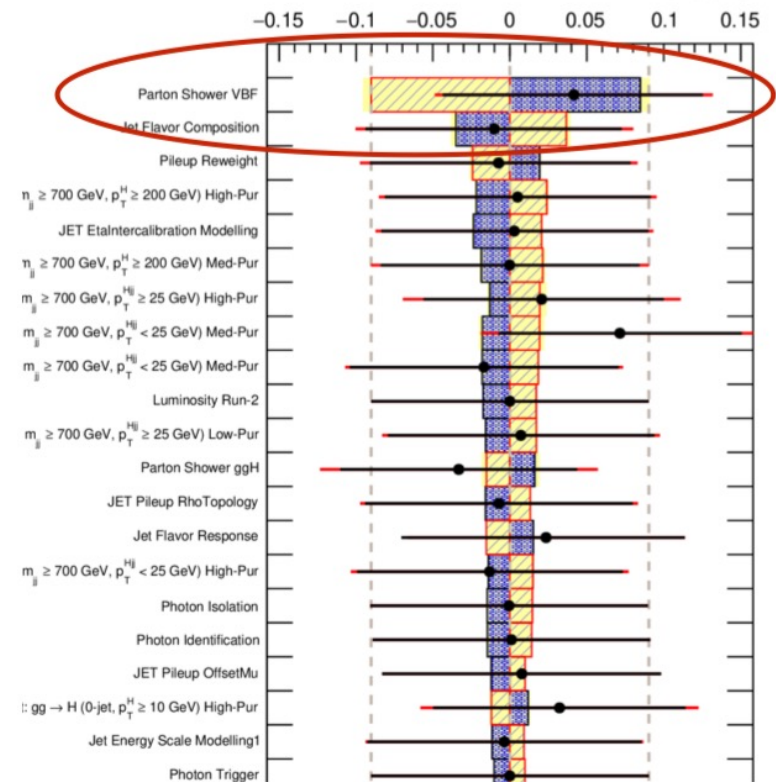
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**ATLAS Preliminary**

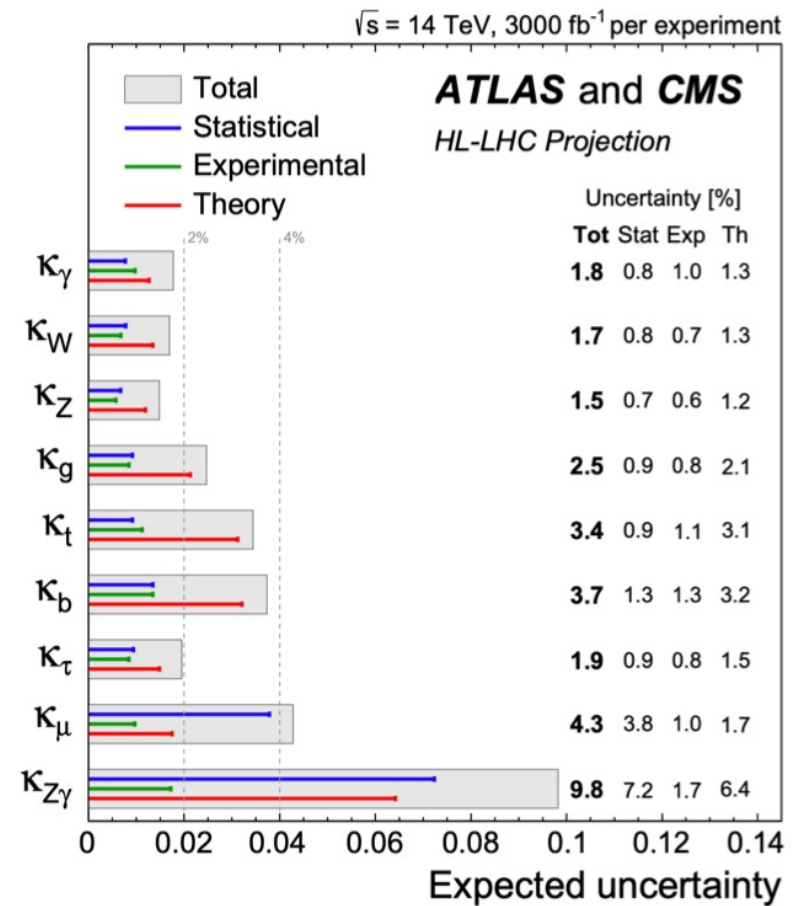
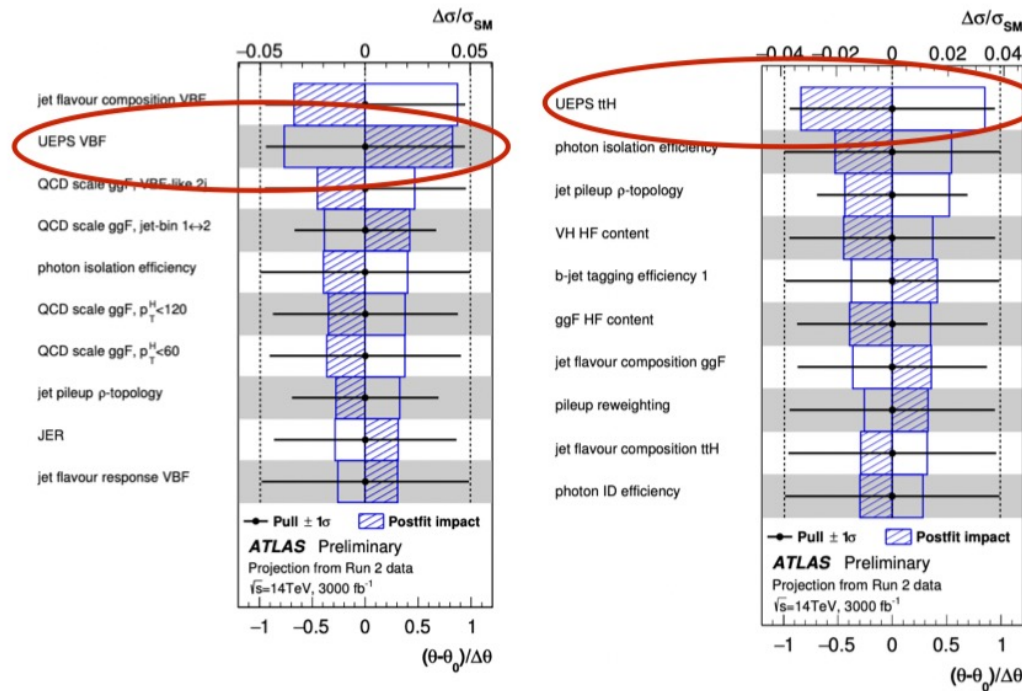
VBF  $\Delta\sigma / \sigma$



Josh McFayden | LH 2021



# PS/Had/UE | HL-LHC





## What to do?

- ▶ *“Why are these uncertainties dominant in so many LHC analyses; can this situation be improved?”*

- Joey Huston

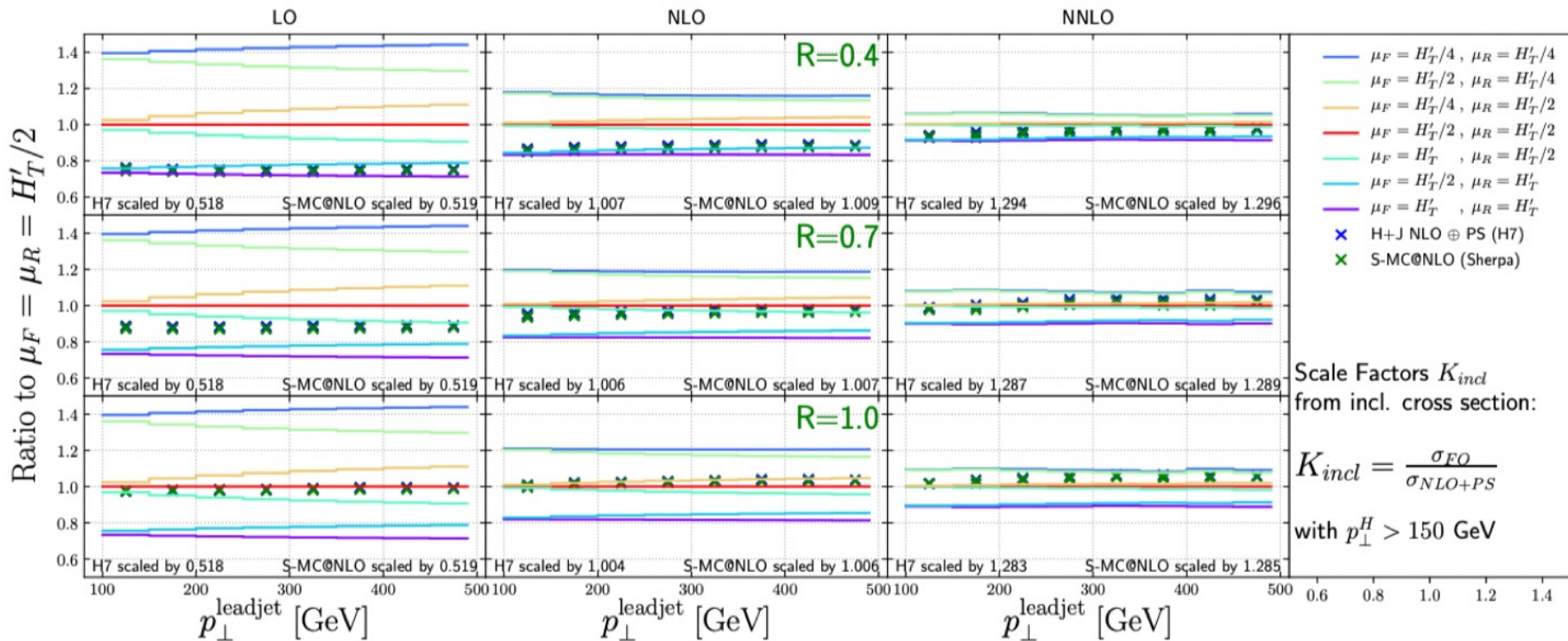
- ▶ Well let's start at the beginning
  - ▶ Do we understand where the large uncertainties are coming from?





# Existing Studies | NLO+PS vs FO

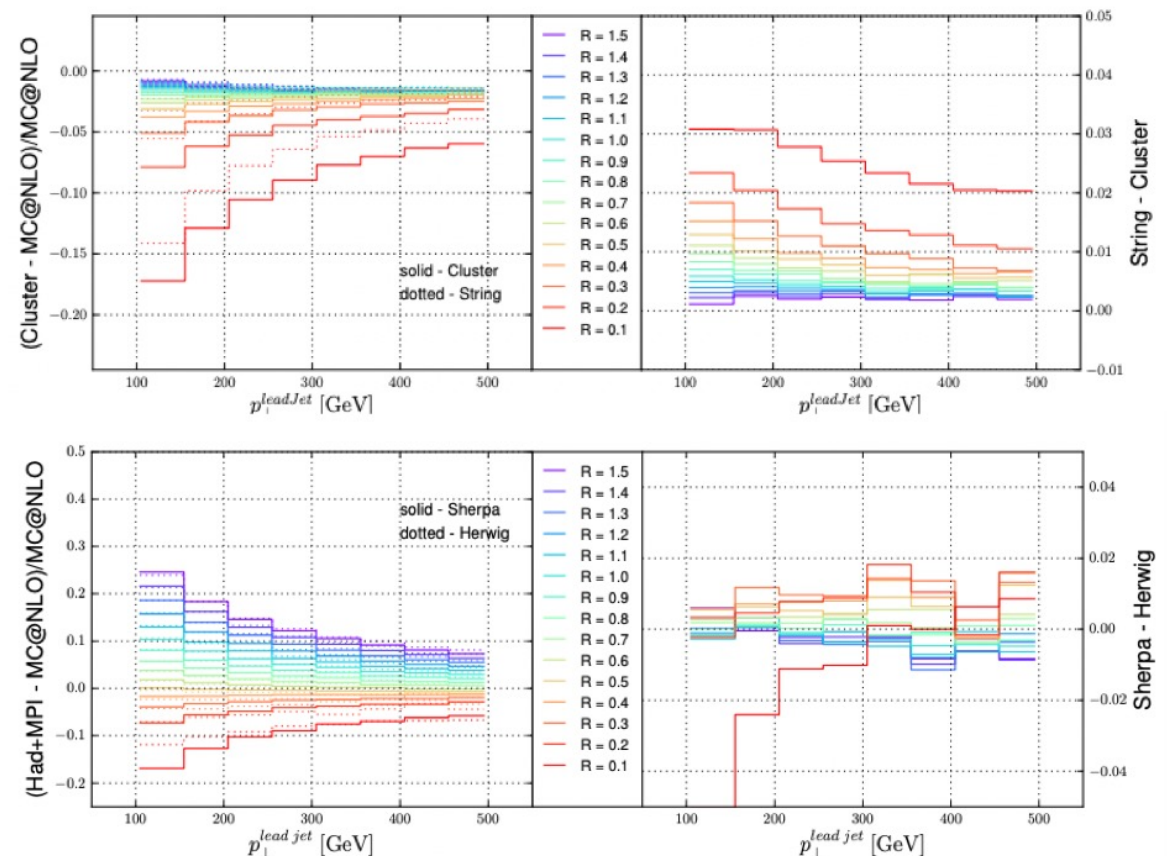
- NLO+PS predictions agree very well with each other and with the FO predictions (to varying degrees depending on the radius parameter).





# Existing Studies | NP corrections

- ▶ Non-perturbative predictions compared as a function of jet size  $R$  and jet  $p_T$
- ▶ Very good agreement between string and cluster fragmentation
- ▶ Also between the full non-perturbative corrections, with fragmentation and MPI, between Sherpa and Herwig.





## What to do?

- ▶ Try to lay out minimal/maximal set of variations needed for a proper assessment of the uncertainties
  - ▶ Two levels:
    - ▶ Wishlist - write down what you want ideally want for each generator
    - ▶ Pheno studies - comparing setups
  - ▶ Essentially an extension of existing LH studies.
- ▶ Link to specific pheno study?
  - ▶ VBS/VBF?
  - ▶ Heavy flavour?
- ▶ Tools: A common hadronisation interface for Herwig/Pythia/Sherpa?
  - ▶ Base class in HepMC or another common package?



## Publishing Unbinned Experimental Unfolded Measurements and Theory Predictions

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There has been a fair amount of progress so far.

This should be an important development.

See Ben Nachman's talk on Wed.

**Miguel Arratia,<sup>a,b</sup> Bogdan Malaescu,<sup>c</sup> Benjamin Nachman,<sup>d,e</sup> Juan Rojo,<sup>f,g</sup> Jesse Thaler,<sup>h,i</sup> and addyourself**

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<sup>b</sup>*Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA*

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<sup>g</sup>*Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, The Netherlands*

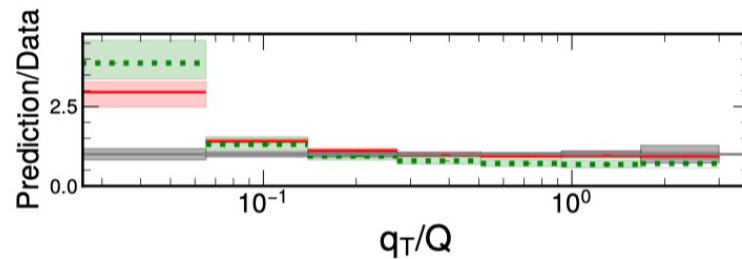
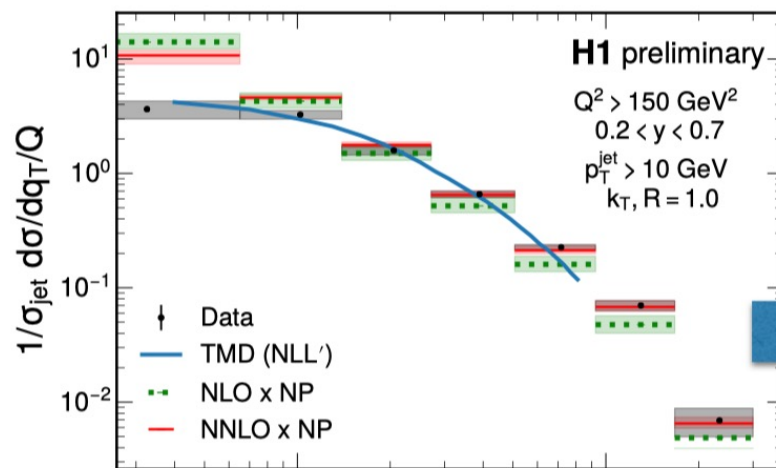
<sup>h</sup>*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

<sup>i</sup>*The NSF AI Institute for Artificial Intelligence and Fundamental Interactions*

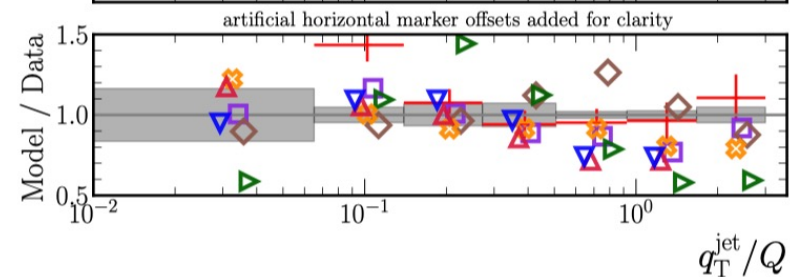
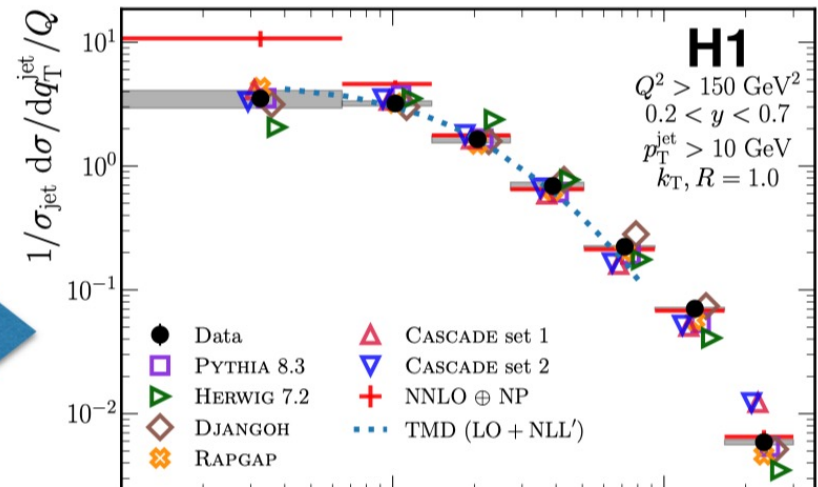
*E-mail:* [bpnachman@lbl.gov](mailto:bpnachman@lbl.gov)

**ABSTRACT:** Machine learning tools have empowered a qualitatively new way to perform differential cross section measurements whereby the data are unbinned and possibly in many dimensions. Unbinned measurements can enable, improve or at least simplify comparisons between experiments and with theoretical predictions. Furthermore, many-dimensional measurements can be used to define observables after the measurement instead of before. There is currently no community standard for publishing unbinned data. While there are also essentially no measurements of this type public, unbinned measurements are expected in the near future given the recent methodological advances. The purpose of this note is to present a proposal for presenting and using unbinned results, which can hopefully form the basis for a community standard to allow for integration into standard analysis workflows. This is foreseen to be the start of an evolving community dialogue, in order to accommodate future developments in this field that is currently rapidly evolving.

## First application to collider data!



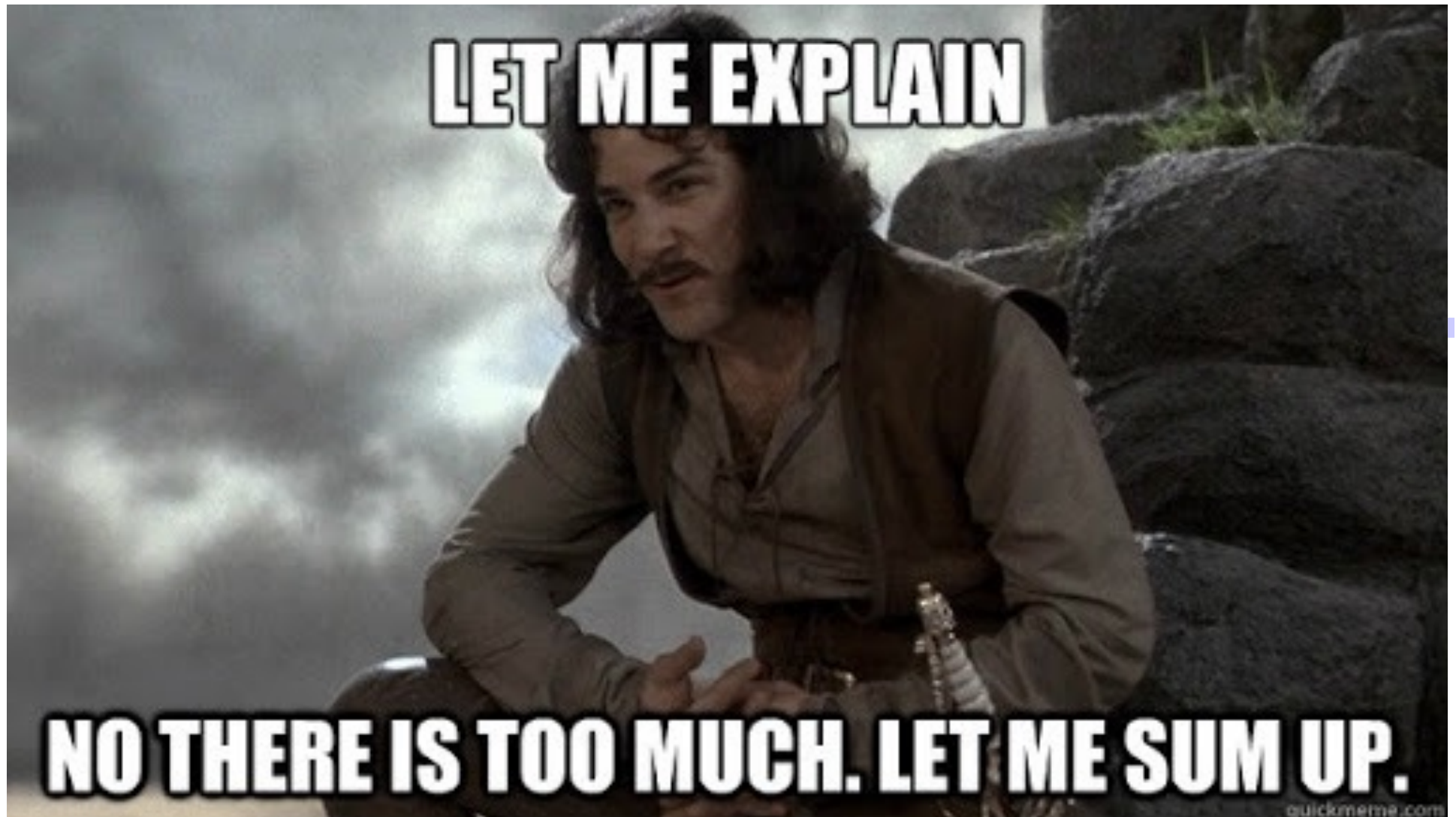
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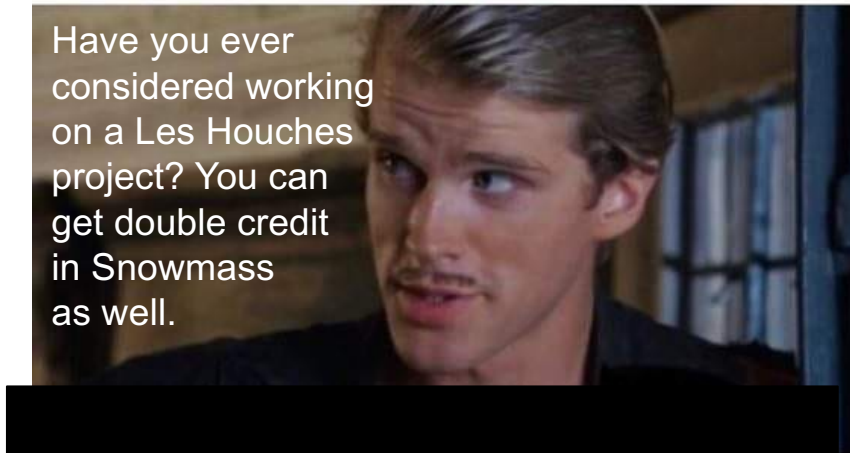


2108.12376  
 (two days ago!)

...finally

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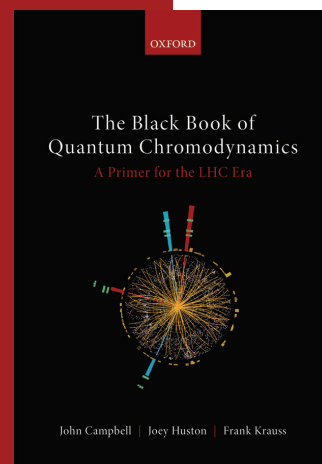


# Dreaming of an in-person Les Houches 2023





due to an open access grant paid by SCOAP<sup>3</sup>, a digital version of the text will soon be available for free



## THE BLACK BOOK OF QUANTUM CHROMODYNAMICS

*A Primer for the LHC Era*

**John Campbell**, Fermi National Accelerator Laboratory

**Joey Huston**, Michigan State University

**Frank Krauss**, Durham University

- Landmark textbook on modern Quantum Chromodynamics
- Pedagogical style, based on lectures, written by practitioners in the field
- Detailed calculations and discussions of all aspects relevant for physics at hadron colliders such as the LHC
- Full of illustrative data
- Clear layout, detailed index, exhaustive references

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